III A. Cable Calibrations

In order to properly measure the performance of CEBAF cavities, it is necessary to accurately characterize the attenuation and return losses of all the interconnecting cables between the cavity and the RF test system.

The required instruments for this procedure are:

1. HP 8753C Network Analyzer.
2. HP 436A Power Meter.
3. HP 8481A Power Sensor Head.
4. UTE Microwave CT-2121-N Circulator.
5. An appropriate length of low-loss RF cable.

These instruments can be found in or on the blue network analyzer cart which is kept in Room 152 when not in use.

For all differential measurements minimize the movement of cables.

Preliminary Measurement Setups

Roll the cart to the dewar in which the cold SRF cavity is housed and connect the components in this fashion:

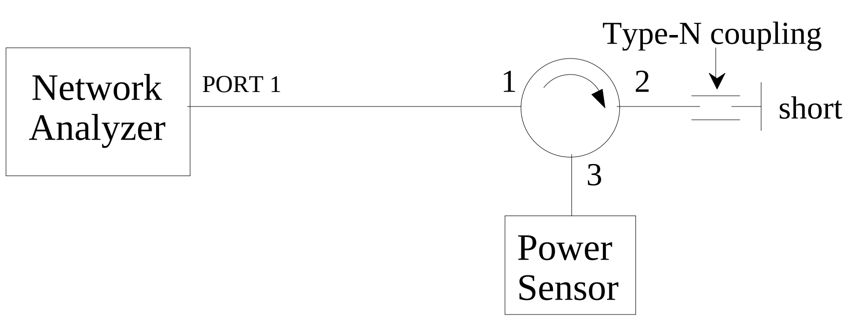

Figure 1. Preliminary Test Setup

1. Open shield lid.
2. Cover roundways with wooden covers.
3. Connect the variable drive coupler cable.
4. Go to the Amp Rack in the VTA and ensure that the 1 Watt Amp power is **ON**.
5. Check that the Cal Factor knob on the Power Meter is set correctly (usually 98%).
6. Connect one end of the cable to the S11 Port (Port 1) on the Network Analyzer and the other end to port 1 of the circulator.

7. Connect the Power Meter Sensor Head to port 3 of the circulator. Using the circulator in the manner depicted in the figure allows the user to measure RF power $_{ref}$lected back into port 2 from a device.
8. Turn on AC power to all the instruments. Allow at least 5 minutes for them to warm up.
9. Go into the control room and select the cavity position to be calibrated (eg. 8 Top) via the rotary switch on the Cavity Select and RF Interlock module.
10. Run the LabVIEW® program **CEBAF Q&E Analysis**, version 39 or higher. This is available under the Apple () Menu if not already running.
11. Enter cavity name in corresponding control (eg IA169. If this is a retest of a cavity, use IA169b, IA169c, etc.). After entering cavity name, rotate cavity selector switch to LOAD, wait 5 seconds, and return to selected cavity position. Entered cavity name will appear in ‘Cavity Name’ indicator.
12. Click the button labeled ‘**Zero Power Meters**’.
13. Click the button labeled ‘**Auto Calibrate Cables**’. A window will pop-up showing the currently selected cavity position, an array of power measurements, a ‘knob’ marked ‘**Atten.**’ (This controls the incident power to the cavity.), and an array of pushbuttons which select desired cable calibration functions.
14. Pre-position the cables (to their intended topplate connections) and check that the connectors are tight.

Incident Power Cable Calibration

15. Connect the Power Sensor to the appropriate Incident Power (1/2” Heliax) cable as shown in Figure 2.

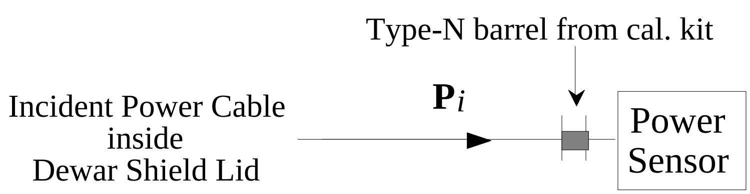

Figure 2. Incident Power Cable Calibration Setup

16. Go into the Control Room and set the Attenuation knob of the Auto Cal panel to **7.0 dB**.
17. Set the Amp Power switch on the Cavity Selection and RF interlock module to **LO**. (Because the shield lid is open, high power operation is not allowed.)
18. Set the RF Enable switch to **ON**.
19. Go out to the dewar and read the Power Meter reading. This reading should be **~70-90 mW**.
20. Go into the control room and click the button marked ‘**Forward Power into Sensor Head**’.
21. An entry window will open. Enter the power reading obtained from the Power Meter into the space provided.
22. Push the button labeled ‘**ENTER**’. The entry window will disappear.

Incident Power Cable Return Loss Calibration

23. Remove the Power Sensor from the cable so that the cable configuration looks like this:

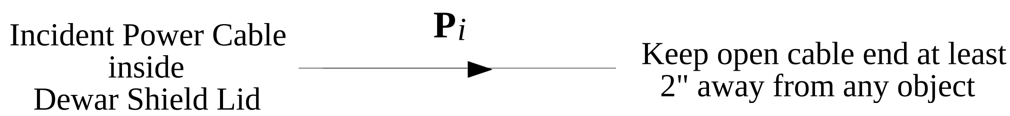

Figure 3. Reflected Power Calibration Setup

24. Go into the control room and click the button marked '**Forward Power into Open**' (Short). A small window will appear briefly that says "**Pi and Pr are measured automatically.**"
25. Set RF Enable switch to **OFF**. Observe that the **RF ON** light is **GREEN**.

Transmitted Power Cable Insertion Loss Calibration

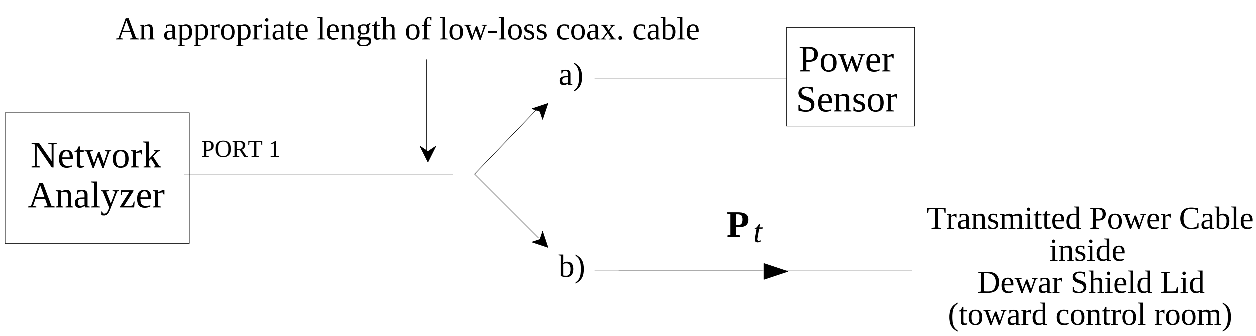

Figure 4. Transmitted Power Cable Calibration Setup

26. Connect the Network Analyzer to the Power Sensor as in a) above, employing the Type-N barrel from the cal kit.
27. This Network Analyzer has an already-loaded instrument state to facilitate these calibration measurements. To use this state, perform the following keystrokes: **[RECALL]** [RECALL CWSET]. The Network Analyzer display should show that the instrument is in the **CW** mode, the frequency is **1497.3 MHz**, and the power is **+24.5 dBm**.
28. Read and record the power level displayed on the Power Meter (80-105 mW).
29. Ca$_{ref}$ully disconnect the Power Sensor from barrel and reconnect barrel to the Transmitted Power cable (as in b) above) that will be attached to the topplate feedthrough.
30. In the Control Room push the button labeled '**Transmitted Power into Control Room**' and enter the power level that was read at the dewar in the entry window provided.
31. Push the button labeled '**ENTER**'. A small window will appear briefly that says "**Pt is measured automatically**." (Pt is typically 2 mW.)
32. Set the Network Analyzer power level to -10 dBm. **[MENU]** [POWER] Enter -10 [X1].

Dewar Insert Transmitted Power Cable Return Loss Calibration

33. Connect the test setup as in a) below.

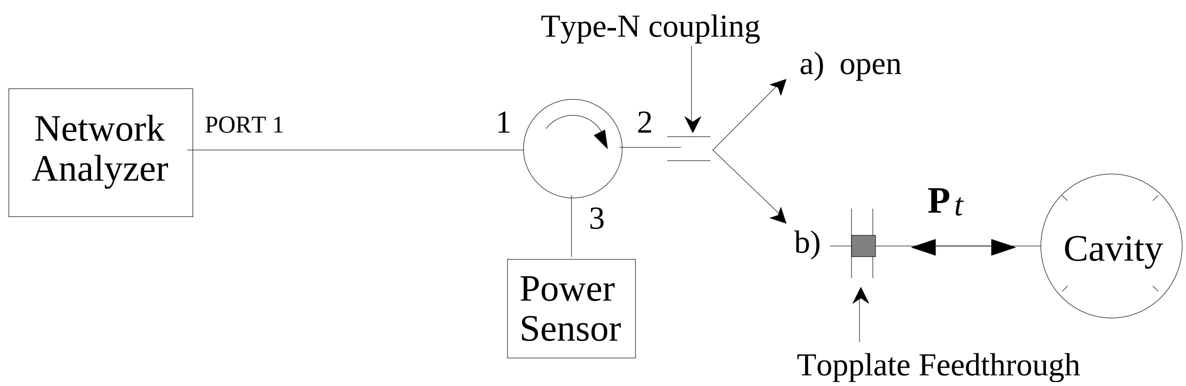

Figure 5. Dewar Insert Transmitted Power Cable Return Loss Calibration Setup

34. Set the Network Analyzer power level to +24.5 dBm. **[MENU]** [POWER] Enter 24.5 [X1].
35. Position cables so that open circulator port is 3” away from Transmitted Power feedthrough on dewar topplate and more than 2” away from any object.
36. With port 2 of the circulator with coupling open, read and record the reading on the Power Meter.
37. Connect port 2 (with coupling) to the topplate feedthrough of the selected cavity (as in b) above) and read and record the power reading.
38. Set the Network Analyzer power level to -10 dBm. **[MENU]** [POWER] Enter -10 [X1].
39. Remove circulator from feedthrough and attach short.
40. Connect the incident and transmitted cables to the cavity under test. Ensure that RF jumper cables are securely connected and tight at both ends. Care must be taken as flex in cables tends to bind connectors on 1/2” Heliax.
41. In the Control Room, push the button labeled ‘**Transmitted Cable Return Losses**’ and enter the power levels that were read at the dewar in the space provided in the entry window.
42. Push the button labeled ‘**ENTER**’ and the window will disappear.

Dewar Insert Incident Power Cable Return Loss Calibration

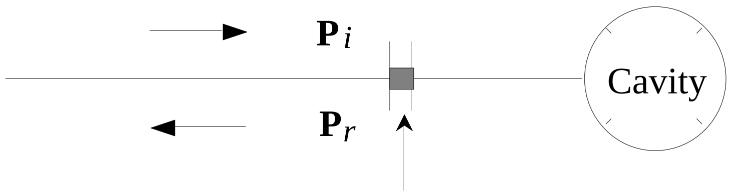

Figure 6. Dewar Insert Incident Power Cable Return Loss Calibration Setup

43. Set the Loop Amp to ‘**OPEN**’.
44. With the Low Power Amplifier selected set the Atten. control to **0 dB**.
45. Set the RF Enable switch to ‘**ON**’.
46. Set the VCO frequency to **1497.3 MHz**.
47. Push the button labeled ‘**Forward Power into Detuned Cavity**’. A small window will appear briefly that says “**Pi and Pr are measured automatically**.”
48. Press the button marked ‘**STOP**’. At this time the window will close and the cable calibrations will be calculated and stored. This creates the current set of cable calibration constraints for the currently selected cavity position.
49. Set the RF Enable switch to ‘**OFF**’.
50. Turn instrument power ‘**OFF**’.
51. Disconnect cable from Network Analyzer and store securely.

[Steps 13, 17, 44, and 46-48 are repeated after initial testing begins and at any time that the operator suspects that cable temperature changes may have changed the cable attenuation slightly.]

III B Preparations

This procedure is to be undertaken only by a qualified Operator.

1. Ensure that RF jumper cables are securely connected and tight at both ends. Care must be taken as flex in cables tends to bind connectors on 1/2” Heliax.
2. Connect control cable to Variable Coupler Drive Motor on topplate.
3. Remove wooden covers from roundways.
4. Close shielding lid. Observe that sweep of lid is clear. **Beware** of loose instrumentation and ion pump high voltage cables. Avoid stepping on the roundways and keep them free of foreign material.
5. In the Control Room, enter the Test Date, Cavity Pair Name, Dewar used for the test, and the Operator’s name in the VTA Operational Safety Log book.
6. Safe Radiation Shielding interlock by pressing **RESET** button on Radiation Interlock system.
7. Run the LabVIEW® program **CEBAF Q&E Analysis**, version 39 or higher. This is available under the Apple () Menu if not already running.
8. Set Attenuation Control to **27 dB**.
9. Set PLL Loop Amp gain to **1**, and close loop with switches in 0° positions.
10. Turn High Power Amplifier **ON**.
11. Set the Amp Power switch on the Cavity Selection and RF interlock module to **HI**.
12. Set the RF enable switch to **ON**.
13. Set Frequency Fine Tuning to mid-range.
14. Turn the Frequency Coarse Tuning knob so that the Frequency Counter reads **1497.0 MHz**.
15. Turn ON power to Variable Coupler Drive Motor control.
16. Set variable coupler to **80%** (20%) for initial test of **Top** (Bottom) cavity in a pair.

III C Establishing Initial Tune-up and Q_{ext2} measurement

This procedure is to be undertaken only by a qualified Operator.

1. Select '**No Phase Trim**' (This button will change to RED.) and deselect **'Phase Set On'** (This button will change to GRAY.)
2. Select '**Set Mixer Level**' to obtain maximum Pt signal input to PLL mixer in order to provide the maximum PLL gain (All attenuators switched OUT and Low Noise Amp switched IN.) during initial acquisition of resonance locking.
3. Manually sweep the Frequency Fine tuning in the range **±250 kHz** about **1497 MHz**. Meanwhile, observe the Ptrans trace on the oscilloscope.
4. On observing any signal on Ptrans, stop and note the frequency.
5. If PLL is in oscillation as evidenced by oscillations in the Phase Error signal, increase attenuation, ie. decrease Pincident, until the loop is stable.
6. Trim frequency to null the Phase Error.
7. Trim Phase manually via Front Panel Control to maximize Ptrans.
8. Trim Phase to minimize P_{ref}.

-- Repeat steps 5 through 8 --

9. Manually determine if coupling, β, is < or > 1 and set Front Panel switch accordingly. Determine coupling by slightly varying insertion of Variable Coupler probe while observing P_{ref}. If P_{ref} decreases with increased probe insertion, then $\beta < 1$. If P_{ref} increases with increased probe insertion, then $\beta > 1$. The best operating ranges for β are (0.7, 0.9) and (1.1, 1.3).
10. Deselect '**No Phase Trim**' (This button will change to WHITE.) and select **'Phase Set ON'** (This button will change to RED.).
11. Set Attenuation to **20 dB**.
12. Select '**Set Mixer Level**'.

-- Repeat steps 5 through 8 --

Having obtained cable attenuation data, one is able to accurately relate power meter measurements to power levels at the cavity. In a CW steady state condition, one determines the dissipated power by simple power accounting. Knowledge of the incident and reflected powers determines the coupling factor , and a decay measurement reveals the loaded .

$$Q_0 = \frac{\omega U}{P_D} = (1 + \beta_1 + \beta_2) Q_L = (1 + \beta_1 + \beta_2)\omega\tau$$

The stored energy is related to the effective accelerating gradient determined by Superfish calculations and confirmed by actual beam tests. Measurement of the transmission probe power for a known stored energy reveals the Q_{ext} of the field probe.

13. Enter 0 in Q_{ext2} control on top monitor.
14. Set Attenuation to **12 dB**.
15. Select '**Set Mixer Level**'.
16. If Multipacting is encountered, refer to troubleshooting section.
17. Select '**Measure and Log**'.
18. Observe consistency of fitted decay curve with the Ptrans decay data. If good agreement, note the calculated Q_{ext2} value. If agreement is poor, refer to Troubleshooting section.

-- Repeat steps 17 and 18 and check for consistency of results --

19. Increase input power (decrease Attenuation) and select '**Set Mixer Level**' and '**Measure and Log**' with accelerating gradient conditions near 2.0 MV/m, 2.5 MV/m, and 3.5 MV/m. Note Q_{ext2} calculations as above. If value are inconsistent, refer to Troubleshooting section.
20. Enter the derived Q_{ext2} value in Front Panel control on top monitor to **enable CW measurements**. Also enter **% error** in the measurement. This error is calculated for each acquisition, and for typical conditions is ≈ 4.5%. Variations in Q_{ext2} Measurements should be consistent with this number and ~(1±0.3)E11.

III D CW Cavity Performance Measurements

This procedure is to be undertaken only by a qualified Operator.

Once Q_{ext2} is determined, cavity performance is measured by the CW method.

1. Enter the Q_{ext2} value (and % error) in the appropriate control.
2. Close shield lid and safe Radiation interlocks if not already done.
3. Turn **ON** rotary beacon light for dewar under test.
4. Set Atten. to **12dB**.
5. Enable high power RF and turn RF enable **ON**.
6. Trim frequency, if necessary, to establish lock.
7. Click the button labeled '**Set mixer level**'.
8. Null Phase Error Signal with Fine Frequency adjustment.
9. Click the button labeled '**Optimize Phase**'.
10. If Multipacting is encountered, refer to Troubleshooting section.
11. As the program idles Q_0, E_{acc} and P_{in} are updated on the monitor.
12. Select '**Measure and Log**' to collect a data point. Analysis is performed automatically and the front panel indicates the results including adding a point on the **Q_0 vs. E_{acc}** plot.
13. For the same power level, reduce input coupling, if possible, and collect another point. If Q_0 improves, use the weaker coupling position, with as low as 0.6. (The variable couplers often contribute the dominate loss for high Q cavities.)
14. If coupling adjustment does not change Q_0, then set a coupling close to 0.92, with **β<1** selected. If coupler range requires overcoupling to cavity, select **β>1** with slide switch.
15. Reduce power and select set mixer level until attenuation on transmission signal is 1± 1dB. (Observe HP Attenuator Driver front panel LED's.)
16. Select '**Measure and Log**'.
17. Reducing power, take several (5 - 8) points, selecting '**Measure and Log**' each time, to map performance to below 1MV/m. Do not select '**Set Mixer Level**'.
18. Increase power back to the level that was set at the beginning of Step 14.
19. Set **Auto Step #** to 60.
20. Select '**Auto Step, Measure and Log**'.
21. Observe measurement progress, when field emission loading decreases the Q_0 to $<5x10^9$, increase the input coupling to achieve greater gradient for the same applied power.

If radiation level inside dewar exceeds 100 mR/hr, stop and inform the Principal Investigator before proceeding. The Principal Investigator is to implement Controlled Area procedures whenever dewar radiation level exceeds 100 mR/hr.

22. If quench is encountered, reduce power and manually increase power until repetitive quenching is

observed.

23. Reduce power and collect data points in the region just below quench. Note the highest stable gradient below quench.
24. If processing is observed, continue applying RF power at near critical coupling. When maximum power produces no change after 10 minutes of sustained operation, processing is complete.
25. Return the coupling to its low field position.
26. Adjust P_{in} for E_{acc} ~5.0 MV/m, open the PLL, detune slightly and repeat the detuned short calibration.
27. Close PLL, regain lock, and select ‘**Set Mixer Level**’.
28. Set the Q_{ext2} value to zero. Vary coupler position slightly and verify that switch is in the correct position.
29. Select ‘**Measure and Log**’.
30. Repeat steps 28 and 29.
31. Confirm that calculated Q_{ext2} is consistent with initial measurements. **If not, resolve the question with the Principal Investigator before proceeding**.
32. Enter best value of Q_{ext2} and % error in the appropriate controls.
33. Record cavity frequency, Q_0, coupler position, and Q_{ext2} in the appropriate places on the **VTA RF Test Summary Sheet**.
33. Select ‘**Auto Step, Measure and Log**’ and complete final run.

III E Passband Characterization

This procedure is to be undertaken only by a qualified Operator.

In order to characterize the lower four passband modes, the following measurement technique is used:

Frequency:

1. Run the LabVIEW® program **CEBAF Q&E Analysis**, version 39 or higher. This is available under the Apple () Menu if not already running.
2. Rotate the '**Coarse**' tuning knob until the display on the frequency counter reads **~1492.3 MHz**.
3. With the shield lid closed, the High Power Amp. selected, and the RF Enable **ON**, set the knob labeled '**Atten**' to **17 dB**.
4. Click the button marked '**Set Mixer Level**'. All the attenuators in the Transmitted Power Network will be switched **OUT** and the Low Noise Amplifier will be switched **IN**. This sets the PLL gain at maximum.
5. Close the PLL by moving the '**0-OPEN-180**' switch to '**0**'.
6. While observing the Transmitted signal on the oscilloscope, trim the frequency ±300 kHz until the PLL acquires the resonance. This is the 4/5 π mode.
7. Record this frequency in the appropriate place on the **VTA RF Test Summary Sheet**.
8. Repeat steps 2 and 6 so the frequency reads **~1480.4 MHz**. This is the 3/5 π mode.
9. Repeat step 7.
10. Repeat steps 2 and 6 so the frequency reads **~1466.7 MHz**. This is the 2/5 π mode.
11. Repeat step 7.
12. Repeat steps 2 and 6 so the frequency reads **~1455.4 MHz**. This is the 1/5 π mode.
13. Repeat step 7.

Q_o and Q_{ext2}:

Q_o and Q_{ext2} characterization of the lower passband modes is accomplished by determining the frequency as above and then using same technique as for π mode. (See III B and III C.) The program senses which mode is being excited and displays the stored energy among the 5 cells.

If test is complete, turn the High Power Amp OFF.

III F. HOM Q Measurements

The HOM loads are required to adequately damp cavity resonances which would otherwise deflect or diffuse the beam during acceleration. The effectiveness of the loads is measured during the cavity pair testing. The distribution of frequencies of HOMs is also important for extrapolation to large SRF applications.

In order to measure the Q's of several important HOMs, the following equipment is required:

1. HP 8753C Network Analyzer
2. HP 7440A Plotter
3. Two appropriate lengths of low-loss RF cable.

These instruments can be found in or on the blue network analyzer cart which is kept in Room 152 when not in use.

Roll the cart to the dewar in which the cold SRF cavity under test is housed and make the following connections:

1. Connect port 1 to the topplate feedthrough marked Incident Power of the cavity under test.
2. Connect port 2 to the topplate feedthrough marked Transmitted Power of the cavity under test.

Turn **on AC power** to all instruments. Allow **at least 5 minutes** for the instruments to warm up.

In the Control Room, set the variable drive coupler so that the coupling probe is **all the way in** the cavity under test's tophat (cavity under test has full coupling).

The Network Analyzer has already-loaded instrument states programmed into memory.

1. Place a piece of paper in the plotter bed and press the hold button.
2. Recall the second HOM measuring mode. **[RECALL]** [RECALL HOM2] If the display trace is off scale, select Auto Scale. **[SCALE REF]** [AUTO SCALE]
3. Configure the Network Analyzer so it can control the plotter. **[LOCAL]** [SYSTEM CONTROLLER]
4. Plot the displayed data. **[COPY]** [PLOT]
5. Note cavity name, position, date, and operator name on plot.

While plotting is under way, the operator may proceed to:

1. Set the instrument state to find the lower HOM peak. **[RECALL]** [RECALL HOM1]
2. If the resonance is not displayed, in will be necessary to increase the sweep span. [SPAN] [›]
3. The lower HOM resonance (~1976 MHz.) should now appear on the CRT. If the peak of the resonance is the highest point on the trace, the center frequency and Q will be displayed on the screen. If the peak is not the highest point, adjust the center frequency **[MKR FCTN]** [MKR fiCENTER] and the sweep

span [SPAN] [fl] until it is. The center frequency and Q will now be displayed on the screen.

4. Record these values in the appropriate place on the **VTA RF Test Summary Sheet**.
5. Increase the sweep span [SPAN] [›] so the higher HOM resonance (~1980 MHz.) is displayed. This resonance usually has a higher peak amplitude so the width subroutine in the Network Analyzer should have no trouble finding the center frequency and Q values.
6. Record these values in the appropriate place on the **VTA RF Test Summary Sheet**.
7. If the two modes are not well resolved in the frequency region of 1974 - 1981 MHz, the HOM loads are doing an excellent job. If the Q can be determined for only one mode, estimate the frequency and Q of the other by rough comparison.

III G. Coupling Hat mode characterization

The cold RF window must, among its other characteristics, have low RF losses in order to contribute an acceptable cryogenic load. The loss character of the window is checked by measuring the Q of the waveguide resonance within the Top Hat and the Fundamental Power Coupler.

In order to avoid errors while performing the fundamental power coupler (FPC) resonance measurement, it is necessary to separate the real and imaginary components of the resulting signal.

To measure the Coupling Hat mode, the following equipment is required:

1. HP 8753C Network Analyzer
2. An appropriate length of low-loss RF cable

This instrument can be found in or on the blue network analyzer cart which is kept in Room 152 when not in use.

The method for performing this measurement is as follows:

Roll the cart to the dewar in which the cold SRF cavity under test is housed and make the following connection:

1. Connect port 1 to the topplate feedthrough marked Incident Power of the cavity under test.

Turn on AC power to the Network Analyzer. Allow **at least 5 minutes** for it to warm up.

In the Control Room, set the Variable Drive Coupler so that the coupling probe is **all the way out** of the cavity under test's tophat. (minimum coupling condition)

The Network Analyzer has an already-loaded instrument state programmed into memory.

1. Set the instrument state to find the Coupling Hat resonance. **[RECALL]** [RECALL HATQ] The display is in complex plane format.
2. Adjust the center frequency **[MKR FCTN]** [MKR fiCENTER] to find the center of the resonance. If the Network Analyzer cannot find the resonance, increase the span [SPAN] [›] so it can. If the Network Analyzer cannot find the resonance, refer to the troubleshooting section.
3. Reduce the span [SPAN] [fl] to a point where the ends of the trace almost meet. A sample plot is shown in figure 1.
4. Rotate the trace to the proper quadrant by adding or subtracting the appropriate amount of phase offset **[SCALE REF]** [PHASE OFFSET] Turn knob so the circle is bisected by the real axis. A sample plot is shown in figure 2.

5. Determine the bandwidth of the resonance (Δf) by changing the format to display the imaginary part of S11 **[FORMAT]** [MORE] [IMAGINARY] and finding the min and max values shown on the trace. Set Marker #2 to the maximum value **[MKR]** [MKR 2] **[MKR FCTN]** [MKR SEARCH] [MAX]. (Marker #1 is already set to search for the minimum value and is the Δ reference.) The bandwidth appears in the upper-right-hand corner of the display. A sample plot appears in figure 3.
6. Record this value (Δf) in the appropriate space provided on the **VTA RF Test summary Sheet**.
7. Now set the Network Analyzer to display the real part of S11. **[FORMAT]** [MORE] [REAL]
8. Determine the center frequency (f_o), tuned{S11(R)} (marker 1), and detuned{S11(D)} (marker 2) absolute S11 values. Make sure absolute values are displayed by turning off the marker Δ mode. [**MKR]** [Δ MODE MENU] [Δ MODE OFF]. A sample plot appears in figure 4.
9. Record the values determined in step 8 {fo, S11(R), and S11(D)}in the appropriate spaces provided on the **VTA RF Test Summary Sheet**.
10. Turn all portable equipment **OFF**.
11. **Store all cables securely**.
12. Return Network Analyzer calibration cart to **Room 152**.
13. Turn High Power Amp **OFF** if not yet done so.